ANSYS Program and Re-validation of the
Thermal Analysis of the Cornell Silicon Crystal

Summary

Thermal analysis of the Cornell three-channel silicon crystal is carried
out using the ANSYS finite element program. Results are in general agreement
with those previously obtained using the Transient Heat Transfer, version B
(THTB) program.[1]

The main thrust of the present study has been to (a) explore the thermal
analysis potentials of the ANSYS program in solving thermal hydraulic problems
in the APS beamline design, (b) compare the ANSYS results with those obtained
by THTB for a specific test crystal, and (c) obtain some cost benchmarks for
the ANSYS program.

On the basis of a limited number of test runs for the silicon crystal
problem, conclusions can be drawn that (a) except for conduction problems with
simple boundary conditions the utility of ANSYS for solving a variety of
three-dimensional thermal hydraulic problems is at best limited, (b) in
comparison with THTB program, ANSYS requires a more detailed modeling (with
increasing computation time) for comparably accurate results, and (c) no firm
statement regarding the cost factor can be made at this time although the
ANSYS program appears to be more expensive than any other code we have used so
far.

1.0 Introduction

In the analysis and design of the various beamline components of the APS
project, availability of reliable and economical numerical codes for heat
transfer and stress analysis is very desirable. While in the case of simpler
problems approximate analytical solutions or numerical codes can be developed,

for more complex problems, in house development, testing, evaluation and verification of numerical programs are not warranted.

A large number of commercial codes to handle thermal hydraulic problems are available. Some of these codes are already installed (but not supported) at ANL. The Transient Heat Transfer, Version B (THTB) that has been extensively used in our analyses is one such code. The System Improved Numerical Differing Analyzer (SINDA) is another capable heat transfer codes available at ANL. Other general-purpose, commercially available, thermal-hydraulic codes include PHOENICS, FLUENT, FLOTRAN. TAP2, THAP and NASTRAN.[2,3]

The capabilities of these thermal codes vary widely and the choice of one over others depends not only on the specific applications but also on such factors as familiarity, reliability, user-friendliness, documentation, support, the operating machine environment, and of course, cost.

For stress analysis applications, similarly, a large number of programs are available.[4]

In addition, there are a number of broad-based general purpose numerical programs that can solve, among others, both thermal and stress problems. These programs are essentially structural analysis codes and their thermal provisions are add-on features which, however, have limited capabilities. ANSYS is one such general-purpose program. It has been available at ANL on the IBM mainframe and its newest version (4.3A) has just been installed on the VAX-8700.*

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*Some of our ANSYS runs were done to test this new interactive version of ANSYS. Identical programs were run at Fermi-Lab. We are not charged for these tests at ANL. ANSYS 4.3A is expected to be available (but not supported) for general use in September 1988.

Like most other structural analysis programs, ANSYS is a <u>finite element</u> codes. The finite element approach is now increasingly used in thermal and fluid analysis[5] where the <u>finite difference</u> methods have traditionally been utilized.

Since both the thermal hydraulic finite difference program THTB and the finite element ANSYS code are available on site, a re-evaluation of the thermal behavior of the Cornell three-channel silicon crystal was undertaken to (1) examine the thermal hydraulic capabilities of ANSYS, (2) verify the THTB solution, (3) develop a basis for cost comparison, and (4) carry out an analysis of the thermal stress in the silicon crystal using ANSYS. The results of the first three tasks are briefly outlined below and the last item is now being pursued.

2.1 Thermal Capabilities of ANSYS

Typical problems encountered in the APS beamline component analysis and design involve heat transfer in three-dimensional complex geometries with convective boundary conditions and various flow regimes. From an extensive examination of the various 'elements' in ANSYS library, as well as discussion with the SWANSON ANALYSIS SYSTEMS, INC. (ANSYS developer) personnel it seems that it is not possible, at least directly, to model a channel flow with radial temperature gradients in three-dimensional conduction-convection problems. This capability is essential for our analysis, and the matter has been brought to the attention of SWANSON consultants. The effects of flow rates and mixing, therefore, cannot be modeled by ANSYS. THTB can simulate these features in a simple fashion.

2.2 ANSYS and Verification of the THTB Analysis

In order to establish the accuracy of the THTB code and the results there of, and also to examine the computational features and merits of the THTB and the ANSYS programs, the Cornell three-channel gallium-cooled silicon crystal problem is further analysed. A uniform x-ray beam of 375 W total power incident at a 14.3°C angle is assumed.

This problem is solved for a variety of flow regimes, boundary conditions, nodal configurations, and code modes. Several of these runs, the ones most pertinent to our comparative analysis of the THTB and ANSYS programs, are summarily included in Table 1 where the maximum observed temperature in the crystal for each case is also included.

2.2.1 THTB Results

In Table 1 the summary descriptions of four sets of THTB runs (Runs #1 to 8) are included. Each set corresponds to a distinct boundary condition and/or flow condition for two typical fluid (or wall) temperatures of 30° and 50°C.

Runs #1 & 2 are the standard runs: they represent realistic models for the silicon crystal cooled by gallium flowing through the three channels at a rate of 1.0 gpm (4.855 ft/sec).

The maximum temperature in the system for the 30°C gallium inlet temperature is 70.1°C, and for the 50°C inlet temperature is 92.7°C. The 22.6°C difference in the maximum temperatures is slightly above the 20°C difference in the flow temperature. This 2.6°C deviation results from the temperature dependency of the silicon properties.

Runs #3 & 4 differ from the standard case (Runs #1 & 2) in that artifically high values of gallium flow rate and specific heat are incorporated to simulate a constant bulk fluid temperature. This case is

necessary for later comparison with the ANSYS computations. The improved convection in these runs reduces the maximum system temperature a few degrees from the corresponding standard Runs #1 & 2.

Runs #5 & 6 in Table 1 are derived to simulate a constant channel-wall temperature by assigning a very large value for the heat transfer coefficient. The maximum temperature in the system is about 10°C less than the corresponding temperature in the gallium-cooled constant bulk fluid temperature case (Runs #3 & 4), and differs from the standard case (Runs #1 or 2) by about 15°C.

In the final THTB runs (Runs #7 & 8) constant channel-wall temperatures are explicitly imposed. The resulting maximum temperatures are slightly lower than the corresponding figures for the simulated constant wall temperature in Runs #5 & 6 (see Table 1).

Taken together, the THTB Runs #1 to 8 display the expected behavior of the thermal system consistently, and in particular show the heat removal efficiency from the crystal from a moderately high convective case (standard Runs #1 & 2) to the maximum possible heat removal rate when the channel wall is kept at a constant temperature (Runs #7 & 8). Noteworthy is the corresponding maximum temperature rise in the crystal that varies from 40.1°C (Runs #1) to 23.4°C (Runs #7) for the fluid and wall temperature of 30°C respectively.

2.2.2 ANSYS Results

The ANSYS pre-processing facilities are used to produce a nodal arrangement for the silicon crystal identical to the one used in THTB runs. This allows a direct comparison between the temperature distributions obtained by the ANSYS and the THTB programs.

Considering the limitations of the ANSYS code, only two of the four cases analysed by the THTB code in the last section can be modeled and solved. They correspond to (a) convection at a constant fluid bulk temperature, and (b) prescribed channel-wall temperatures.

The ANSYS Runs #9 & 10 in Table 1 yield the maximum temperatures in the silicon crystal for constant fluid bulk temperature of 30 and 50°C respectively. While the difference between the two maxima of 56.1°C and 78.1°C is 22.0°C and, therefore, consistent with the THTB results, the temperatures themselves are not. For a fluid bulk temperature of 30°C, THTB yields a maximum system temperature of 66.8°C (Run #3) while ANSYS gives a 56.1°C (Run #9) temperature, about 16% lower.

This divergence of solution, particularly in view of the identical system specifications and nodal arrangement used in THTB and the ANSYS requires an explanation (note that tight and identical convengence criteria are used in both cases).

The difference in the results stems from the fact that ANSYS and THTB utilize two different numerical scheme based on two distinct conceptual approach to the formulation and solution of the problem. That a firm and general statement regarding the accuracy of one solution over the other cannot be made is due to a multiple of factors ranging from problem specifications and boundary conditions to the precise methodology and algorithm used in the finite element and finite difference methods.

In our particular problem of thermal analysis of the silicon crystal the discrepancy between the THTB and ANSYS results is attributable to the inaccuracy in the ANSYS solution since we have every indication that the THTB results are both consistent (as, for example, Runs #1 to 8 in Table 1 indicate) and accurate (as indicated by our extensive checks and cross-checks

of the results as well as examination of energy conservation and convergence criteria[*]).

With the assurance of accuracy in the THTB results (which is further verified as described below) the source of discrepancy between THTB and the ANSYS results may lie in the size of the elements used in the ANSYS program. Additionally, large aspect ratios are thought to have detrimental effects on the accuracy of the ANSYS results; such effects are not expected in THTB program barring steep material property and temperature gradients.

Thus, for more accurate results another ANSYS run in which the silicon crystal is re-meshed taking a total of 8960 nodes (instead of the previous 1232) is attempted (Run #11, Table 1). In doing so, we almost double the number of nodes in each direction and reduced some of the large element aspect ratios. As shown in Table 1, for a fluid bulk temperature of 30°C a maximum system temperature of 64.5°C is obtained. This is sharply different from the 56.1°C obtained with fewer nodes, and shows that in this particular case (a) the accuracy of the ANSYS results is substantially improved when a very large number of nodes is utilized and, (b) the improved solution yields a maximum temperature in the system which differs from the corresponding THTB solution (Run #3) by only 3%. This is an independent verification of the THTB results.

The improved accuracy in the ANSYS results, however, comes at the expense of a substantial increase in the computation time, from 200 to 6000 CPU seconds or a thirty-fold increase. The cost of running this program on the VAX-8700 varies from $660 (for daytime interactive) to an absolute minimum of $290 (for weekend batch).[**]

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*Energy is automatically conserved in the ANSYS program and thus cannot be used as a means of checking the accuracy of the results. Conservation of energy, however, does provide an independent and extremely useful means for examining the THTB results.

**Figures are based on a minimum royalty fees of 4.1C/CPU seconds and $250/hr($25/hr) of CPU time charge for interactive (weekend batch) programming on the VAX-8700 machine.

As indicated elsewhere in this memorandum, no attempt has been made to optimize this last ANSYS run. Appropriate preparation of the problem can substantially reduce the computation expenses, but this will be at the expense of staff time required in the tedious task of devising optimal problem description. Two additional ANSYS runs (Runs #12 & 13) with constant channel-wall temperatures corresdponding to the THTB Runs #7 & 8 respectively, are included in Table 1. The 8960 node versions are not run for these cases for reasons of economy

This section can be summarized by stating that (a) ANSYS cannot directly solve the silicon crystal problem realistically since it cannot treat the channel flow in the problem but (b) it can solve the problem if simple convective boundary conditions on the channel walls are imposed, however, (c) to obtain comparatively accurate results a much finer nodal description of the silicon crystal than the one in THTB analysis must be used and (d) this requires a much higher computational expense which (e) can be somewhat reduced at the expense of staff time required for problem optimization.

2.3 THTB and ANSYS Cost Basis

The approximate CPU seconds used in the THTB and ANSYS runs are included in Table 1. Pre-and post-processing times are not included in the case of ANSYS runs.

While no attempt was made at optimizing the detailed ANSYS program Run #11 (Table 1) its long computation time (Table 1) is indicative of the expenses involved. We guesstimate that by taking appropriate optimization measures in modeling and preparation, this computation time can be reduced, perhaps by two third. Our aim here has not been to run an efficient program, rather to obtain a feel for the computational expense.

The substantial difference in computation time between THTB and ANSYS (for comparable accuracy in results), apart from the optimization factor alluded to above, lies in the fact that these two numerical codes essentially utilize different formulation and solution approaches. As mentioned before, THTB uses a finite difference method while ANSYS is a finite element program. There seems to be no general theory to explain why one approach yields better results than another for a given problem and configuration.[6] It very much depends on the specifics of the problem being considered and the precise manner in which computations within the codes are performed, although under certain conditions, finite element solutions should yield better results.

THTB is a no-usage fee program but ANSYS carries a minimum charge of 4.1c per CPU second on the VAX-8700 (with $1000 per month minimum charge, site wide). This is, of course, in addition to the computer time expenses.

In summary, it is difficult to assess cost figures for ANSYS on the basis of the limited number of tests runs, but the data in Table 1 may be used as rough yardsticks.

3. Conclusions

Previously obtained THTB results for a gallium-cooled silicon crystal are verified using the ANSYS program. ANSYS can be used to solve various heat transfer problems, although its capabilities are limited necessitating in certain cases the use of other, more specific, heat transfer and fluid codes. The maximum temperature rise in an experimental 3-channel Cornell silicon crystal subject to synchrotron radiation has been verified by both ANSYS and THTB codes.

TABLE 1: Various THTB and ANSYS runs

Run #	Code Used	Fluid Temp. (°C)	Solid-Fluid B.C.	Heat Transfer Coeff. H(Btu/ft²-°F)	Flow Rate ft/sec	No. of Nodes in Model	Maximum System Temperature, °C	Approximate CPU Seconds Used on VAX-8700	Comments
1	THTB	30, inlet	Convective	10,000	4.9	1232	70.1	700	Standard cases
2	THTB	50, inlet	Convective	10,000	4.9	1232	92.7	700	
3	THTB	30, inlet	Convective	10,000	1,000	1232	66.8	700	high flow rate and specific heat are used to <u>simulate</u>
4	THTB	50, inlet	Convective	10,000	1,000	1232	89.4	700	a constant fluid bulk temperature for fluid
5	THTB	30, inlet	Convective	99,999	1,000	1232	55.1	700	same as Runs # 3 and 4, except a high heat transfer
6	THTB	50, inlet	Convective	99,999	1,000	1232	77.4	700	coefficient value is used to <u>simulate constant channel-wall temperature</u>
7	THTB	Not Applicable	T_W=30°C	Not Applicable	Not Applicable	1232	53.4	700	No flow; channel walls are kept at a constant temperature
8	THTB	Not Applicable	T_W=50°C	Not Applicable	Not Applicable	1232	75.6	700	
9	ANSYS	30, Constant bulk temp.	Convective	10,000	Not Available	1232	56.1	200	ANSYS runs using the same nodal configuration as in THTB
10	ANSYS	50, Constant bulk temp.	Convective	10,000	Not Available	1232	78.1	200	
11	ANSYS	30, Constant bulk temp.	Convective	10,000	Not Available	8960	64.5	6000	detailed version of Run #9; almost eight times as many elements are used
12	ANSYS	Not Applicable	T_W=50°C	Not Applicable	Not Available	1232	47.9	200	ANSYS counterparts of THTB runs #7 and 8
13	ANSYS	Not Applicable	T_W=50°C	Not Applicable	Not Available	1232	69.6	200	

*A node is here defined as a coordinate location in space. This statement is necessary to reconcile the different terminology used in finite element and finite difference methods.

References

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